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Depositional facies and radiocarbon ages of a drill core from the Mekong River lowland near Phnom Penh, Cambodia: evidence for tidal sedimentation at the time of Holocene maximum flooding

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Abstract

The depositional facies and radiocarbon ages of a long Holocene sediment core (KS) from Cambodia are reported here to clarify the sedimentary environments of the Mekong River delta system at the time of Holocene maximum flooding by the sea. The 30.7-m-long KS core, from the upper Mekong River lowland about 20 km southeast of Phnom Penh, penetrated five depositional facies, A to E in ascending order. Facies A is cross-laminated fluvial sand. Facies B is laminated, very fine sand with mud drapes. Facies C to E are salt marsh, flood-plain and natural-levee deposits, characterized by a succession of peat, organic clay, and reddish brown silt. Facies B dates to 9.0 to 7.5 ka and is interpreted as aggradational tidal deposits, 16.5 m thick, deposited during a rapid rise of sea level; these deposits became overlain by an accumulation of salt marsh and flood-plain deposits during the subsequent period of slowly rising and then falling sea level. The maximum flooding surface lies in the Facies B interval. The presence of tidal deposits implies that the core site, about 230 km inland from the present river mouth, was near the shoreline and experienced strong tidal influences during the early Holocene.

Keywords: Aggradation; Delta; Highstand; Mud drapes; Peat; Regression; Sea-level rise; Transgression

1. Introduction

Over the last several thousand years of relative sea-level highstand, Asian megadeltas, which characterize coasts where large rivers enter the sea, have prograded rapidly seaward as a result of abundant sediment discharge from rivers, resulting in extensive coastal lowlands (e.g., Somboon and Thiramongkol, 1992; Stanley and Warne, 1994; Saito, 2000; Hori et al., 2001; Roberts and Sydow, 2003; Tanabe et al., 2003a, b). This period of progradation was preceded by transgression due to a rapid sea-level rise, during which sediment deposition in coastal areas generally occurred in estuarine systems (Boyd et al., 1992). Attributes of the transitional period from transgressive estuary to regressive delta, such as timing, sedimentary environment, and shoreline position at the time of maximum flooding are regionally dependent, reflecting water and sediment discharge levels, basin morphology, tectonics, and coastal hydrodynamics. In the Red River delta, the shoreline started to prograde around 8.5 ka from more than 80 km inland from the present coast (Hori et al., 2004). The Changjiang River system has prograded since ca. 8 ka, at which time the shoreline was located 300 km inland (Hori et al., 2002).

The Mekong River is the world's ninth largest river in annual sediment discharge, and tenth largest in water discharge. The coastal lowland along the river in Cambodia and southern Vietnam is extensive. The lower portion of the lowland is a delta plain, which prograded rapidly over 6–7 ka (Ta et al., 2002; Tanabe et al., 2003c). Although Ta et al. (2001) studied a drill core that penetrated the transgressive estuarine deposits in the incised valley in the subsurface of the present Mekong River delta, the absence of a detailed sedimentological study in the Cambodian lowland has prevented reconstruction of the whole picture of the Mekong River system at the time of maximum flooding. This paper reports the depositional facies and radiocarbon ages of a long (30.7-m) drill core obtained from the upper Mekong River lowland near Phnom Penh, reconstructs the Mekong River depositional system at the time of the culmination of the post-glacial marine transgression and predicts the subsurface stratigraphy of the Cambodian lowland.

2. Geological Setting

The Mekong River originates in Tibet and flows 4.6×10^3 km (National Astronomical Observatory, 1999; Hori, 2000) before discharging into the South China Sea. The area of the Mekong River basin is about 8.0×10^5 km^2 (Milliman and Syvitski, 1992), covering portions of the territories of six countries: China, Myanmar, Thailand, Laos, Cambodia, and Vietnam (Fig. 1A). The annual water and sediment discharges are

470 km^3 and 1.6×10^8 t, respectively, tenth and ninth largest in the world.

Near Phnom Penh, the Mekong River divides into the two main distributary channels of the lower portion of the river system: the Bassac River and the main stream of the Mekong River (Fig. 1B). A huge lowland lies along these channels. In Cambodia, this lowland, which is bordered by mountains and alluvial fans, is 30–40 km wide and generally less than 10 m in elevation. Southward, in southern Vietnam, it spreads out to form a delta plain. During the rainy season, the lowland is flooded by river overbank flow, except near the shoreline, where beach ridges and sand dunes are well developed. The tidal range in the Mekong River delta is 2.4–2.6 m on average with a maximum of 3.2–3.8 m (Gagliano and McIntire, 1968; Coleman, 1981; Wolanski et al., 1996; Nguyen et al., 2000). At high tide during the dry season, saltwater intrudes up to several tens of kilometers upstream from the river mouth (Fig. 1B; Hori, 2000).

The Holocene evolution of the Mekong River delta in Vietnam has been well studied by examining the geography and subsurface geology of the delta plain (Nguyen et al., 2000; Ta et al., 2002; Tanabe et al., 2003c). The delta has prograded more than 200 km over the last 6–7 ka because of the abundant sediment supply from the Mekong River. The situation during the maximum flooding by the sea, preceding delta progradation, however, has not yet been constrained because the shoreline had probably retreated into present-day Cambodia, where the subsurface Holocene sediments are insufficiently known for interpretation of the sedimentary system.

By compiling studies reconstructing the Holocene relative sea-level curve along the western margin of the South China Sea (Geyh et al., 1979; Tran and Ngo, 2000; Lam and Boyd, 2001), we can roughly estimate the sea-level history of the Mekong River lowland (Fig. 2). During the Holocene, relative sea level in this area initially rose, but the rate of rise gradually decelerated until 5–6 ka, becoming a stillstand, with a subsequent slight sea-level fall of a few meters.

3. Samples and Methods

A 30.7-m-long drill core, the KS core, was obtained from the Mekong River flood plain (long 105˚07.8'E, lat 11˚28.2'N; c.a. 7 m a.s.l.) in Kean Svay District, Kandall Province, Cambodia, about 20 km southeast of Phnom Penh (Fig. 1B) by using the pushing and rotary drilling methods. The recovery of the KS core was about 60%. The core was split, described, and photographed to determine the depositional facies. The facies were classified on the basis of grain size, color, physical sedimentary structures, and content of organic material. Diatoms and foraminifera were not preserved in the core. To measure the mud content, samples of 5-cm-thick intervals were sieved through a 0.063-mm mesh. The core was sliced and placed in a plastic case (1 cm thick, 5 cm wide, and 20 or 25 cm long) to take soft X-radiographs. Radiocarbon ages of eight plant fragments and two samples of organic mud were determined by Beta Analytic, Inc. The obtained conventional radiocarbon ages were calibrated to calendar ages using CALIB rev. 5.0.1 (Stuiver and Reimer, 1993) and the data set intcal04.14c (Reimer et al., 2004).

4. Depositional Facies

4.1 Description

Five depositional facies, A to E, in ascending order, were recognized in the KS core (Fig. 3).

Facies A is more than 40 cm thick and comprises the basal part of the KS core (Fig. 3). It is composed of cross-laminated, micaceous very fine sand (Fig. 4A) and contains mud clasts less than 5 mm in diameter. The mud content is less than 10% (Fig. 3).

Facies B overlies Facies A, but the boundary was not constrained because of the poor recovery of this part of the core. This facies is about 16.5 m thick and composed of horizontally to low-angle cross-laminated very fine sand with mud drapes (Figs. 4B and 5A). Ripple cross-lamination is rare, but it is bidirectional where present (Fig. 5B). Mud drapes are thinner than 5 mm in general and occur rhythmically. They are generally gray, but they are reddish brown in the basal sediments and yellowish gray in the uppermost part of the facies. The uppermost part of this facies is muddy and comprises lenticular beds of sandy silt with intervening lenticular, about 1-mm-thick sand layers (Fig. 4C). The mud content is less than 40% in the sandy parts and 40%–80% in the muddy parts.

Facies C overlies Facies B with a gradual boundary and is characterized by a 5-m-thick alternation of peat with graded sand to silt (Fig. 4D). The peat is composed of laminated gray clay to silt containing plant fragments several centimeters wide and long. The intervening sandy layers are composed of yellowish silt and sand and show normal or inverse grading without distinct lamination. The contact between the peat and graded layers can be either erosional or gradual (Fig. 5C). The mud content is more than 60% in the peat and 40%–70% in the graded layers.

Facies D overlies Facies C with a sharp boundary and is composed of greenish to yellowish gray organic clay and silt (Fig. 4E). Plant fragments are scarce. Unfortunately, part of this facies was completely deformed during sampling, becoming mixed with the overlying reddish-brown sandy silt (Facies E). The thickness of this facies is, therefore, poorly known. This facies is recognized here by the presence of greenish-gray clay, and its thickness is assumed to be about 3 m. The mud content is more than 80%.

Facies E is composed of reddish-brown sandy silt about 4 m thick and occupies the uppermost part of the core (Fig. 4F). This facies contains spherical concretions several centimeters in diameter, and it is similar to the surface sediment of the flood plain to natural levee around the drill site. The mud content is 60%–90%.

4.2 Interpretation

The insufficient recovery of Facies A makes it difficult to interpret its sedimentary environment. However, because of the absence of features associated with marine deposition, such as mud drapes, bidirectional cross-lamination, and wave ripples, and because of the abundance of mica, the cross-lamination of this facies is inferred to have formed by the migration of dunes in a fluvial setting.

Facies B is characterized by well-developed mud drapes. The rhythmic alternations of sand layers with thin mud drapes imply transportation and deposition of sand by flood and ebb tidal currents, followed by the settling of suspended mud during the slack-water periods. The ripple cross-lamination is bidirectional, suggesting an oscillatory flow. This facies is therefore interpreted as having formed in an intertidal to subtidal tide-influenced environment.

The peat in Facies C suggests an intertidal to supratidal salt marsh setting. The intervening graded sand layers are considered to have formed by the deposition of the suspended load from overbank flooding of the river. Some boundaries between sand and peat are gradual, suggesting that at least some of the plant fragments were supplied by river floodwaters. These features indicate that the sedimentary environment of Facies C is a salt marsh influenced by river flooding.

Facies D and Facies E are interpreted as flood-plain deposits and flood-plain to natural-levee deposits, respectively, because Facies E is continuous with the surface sediment of the present flood plain to natural levee and Facies D overlies Facies C without intervening marine deposits.

5. Radiocarbon Ages

The radiocarbon ages (Table 1; Fig. 2) suggest that most of the sediments in the KS core accumulated during the period of relative sea-level rise in the early Holocene. Two dates on organic sediments from Facies B indicate that the depositional age of this facies is 9.0–7.5 ka. Although the ages of the plant fragments in Facies C scatter between 8.0 and 7.3 ka, those of samples Beta-192754 and Beta-192748 are used here because they are relatively young and because the samples experienced less reworking before their final burial and thus are assumed to better reflect the depositional age. Therefore, Facies C is considered to have formed from 7.5 to 7.2 ka. The age of a plant fragment from the uppermost part of Facies D is 682–650 cal yr BP, which is much younger than the top of Facies C, suggesting that the accumulation rate of Facies D was low, less than 50 cm ka^{-1}. Facies E accumulated during the last 700 years.

6. Discussion

Integration of the facies interpretation and radiocarbon dating clarifies the temporal evolution of the Holocene sediments in the KS core in relation to the relative sea-level changes (Figs. 2 and 3). The difference between the relative sea-level and sediment accumulation curves (Fig. 2) indicates the approximate depositional depth, the water depth at which the deposits were formed and preserved (e.g., Tamura, 2004). It suggests that both Facies B and C accumulated several meters below sea level, slightly different from the interpretation of these facies (Fig. 3). However, if the influence of sediment compaction would be considered, the sediment accumulation curve shifts upward, and then the actual depositional depth is calculated much shallower. Thus, the discrepancy between the interpretation of depositional facies and the depositional depth calculated on the basis of Fig. 2 is not significant.

The seaward shifting of the depositional environment from fluvial to a tide-influenced setting, revealed by the transition between Facies A and B, is related to the transgression associated with the rapid rise of relative sea level in the early Holocene. On the other hand, Facies B and C suggest an upward shallowing of water depth from subtidal to intertidal or supratidal, reflecting progradation of the shoreline caused by an abundant sediment supply, although the relative sea level was still rising. Thus, the maximum flooding surface is considered to be somewhere within the Facies B interval. The thickness of Facies B is 16.5 m, which is much more than the presumed water depth of the subtidal to intertidal environment because even the maximum tidal range in the present Mekong River delta is no more than 3.2–3.8 m (Gagliano and McIntire, 1968; Coleman, 1981; Wolanski et al., 1996; Nguyen et al., 2000). This implies that the rate of relative sea-level rise was approximately equal to the accumulation rate, thus preserving the accommodation space during the deposition of Facies B, as is also suggested by the rough correspondence between the depositional curve and the relative sea-level curve for the South China Sea (Fig. 2). Facies C and the uppermost part of Facies B accumulated faster than the rate of sea-level rise, which had considerably decelerated at this stage (Fig. 2), resulting in the shallowing of the depositional environment. Facies D and E formed after relative sea level had stopped rising, when the Mekong River delta was rapidly prograding further downstream (Ta et al., 2002; Tanabe et al., 2003c). The low accumulation rate of Facies D, 50 cm ka^{-1}(Fig. 2), is curious because the overlying Facies E shows an accumulation of 4 m during the last 700 years. The sudden increase in accumulation rate may have been related to human impacts, relative sea-level change, or expansion of the lower Mekong delta, but its interpretation requires additional data.

The discovery of tidal deposits in the KS core, 70 km inland from the border with Vietnam (Fig. 1B), suggests that the shoreline may have retreated into Cambodia in the early Holocene, during the maximum flooding period. Along the present Mekong River, saltwater reaches several tens of kilometers upstream from the river mouth during the dry season (Fig. 1B), suggesting that a wide area is influenced by tides and making it difficult to precisely reconstruct the shoreline position based on the record of tidal deposits. However, as a rough estimation, the shoreline had probably retreated to a point several tens of kilometers or less downstream from Phnom Penh before the progradation of the Mekong River delta. At that time, most of the present lowland area in Cambodia experienced tidal effects, implying the extensive presence of Holocene tidal and shallow marine deposits in the subsurface of the Cambodian Mekong River lowland.

7. Conclusions

This first report of a long drill core of Holocene sediment in Cambodia, obtained from a site 20 km southeast of Phnom Penh, suggests tidal influence in the upper Mekong River lowland around the period of Holocene maximum flooding, which is estimated to have occurred between 9.0 and 7.5 ka. The core is composed of fluvial deposits, subtidal to intertidal deposits with mud drapes, and salt marsh, flood-plain and natural-levee deposits, in ascending order, which reveal first transgression and then regression. The maximum flooding surface is, therefore, within the 16.5-m-thick interval of tidal deposits, which formed during a period of rapid rise of relative sea level. The discovery of tidal sedimentation near Phnom Penh suggests that extensive Holocene tidal and shallow marine deposits are present under the upper Mekong River lowland in Cambodia.

Acknowledgements

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Access code	Core depth (m)	Elevation (m)	Facies	Sample	Conventional ^{14}C age (yr BP)	δ 13C (permil)	Calibrated age (1σ) (cal yr BP)	Probability	Calibrated age (2σ) (cal yr BP)	Probability
Beta-192747	4.07	2.93	D	Plant fragment	700±40	-26.7	682–650	0.795	699–629	0.716
							582–569	0.205	601–559	0.271
									710–703	0.009
									721–719	0.004
Beta-192748	7.08	-0.08	C	Plant fragment	6250±40	-27.9	7253–7161	1.000	7265–7152	0.767
									7123–7021	0.233
Beta-192749	7.90	-0.90	C	Plant fragment	6620±40	-27.9	7521–7475	0.585	7571–7439	1.000
							7566–7534	0.415		
Beta-192750	8.33	-1.33	C	Plant fragment	6470±40	-29.1	7361–7329	0.425	7441–7292	0.989
							7397–7368	0.343	7459–7450	0.011
							7430–7413	0.232		
Beta-192751	9.08	-2.08	C	Plant fragment	7130±40	-28.1	7998–7935	1.000	8020–7924	0.866
									7901–7866	0.134
Beta-192752	9.60	-2.60	C	Plant fragment	7030±40	-30.3	7933–7888	0.516	7954–7787	0.992
							7882–7837	0.484	7771–7764	0.008
Beta-192753	10.48	-3.48	C	Plant fragment	7150±40	-28.6	8003–7949	1.000	8029–7929	0.952
									7895–7873	0.048
Beta-192754	12.27	-5.27	C	Plant fragment	6550±40	-30.0	7483–7428	1.000	7519–7419	0.924
									7564–7536	0.074
									7347–7345	0.002
Beta-192755	12.65–12.75	-5.65–-5.75	B	Organic sediment	6760±40	-25.7	7625–7584	0.721	7675–7571	1.000
							7656–7636	0.279		
Beta-192756	28.10–28.15	-21.10–-21.15	B	Organic sediment	8180±40	-22.0	9139–9030	0.806	9262–9021	1.000
							9202–9179	0.134		
							9236–9225	0.059		

Table 1

Results of radiocarbon dating of plant fragments and organic sediment in the KS core.

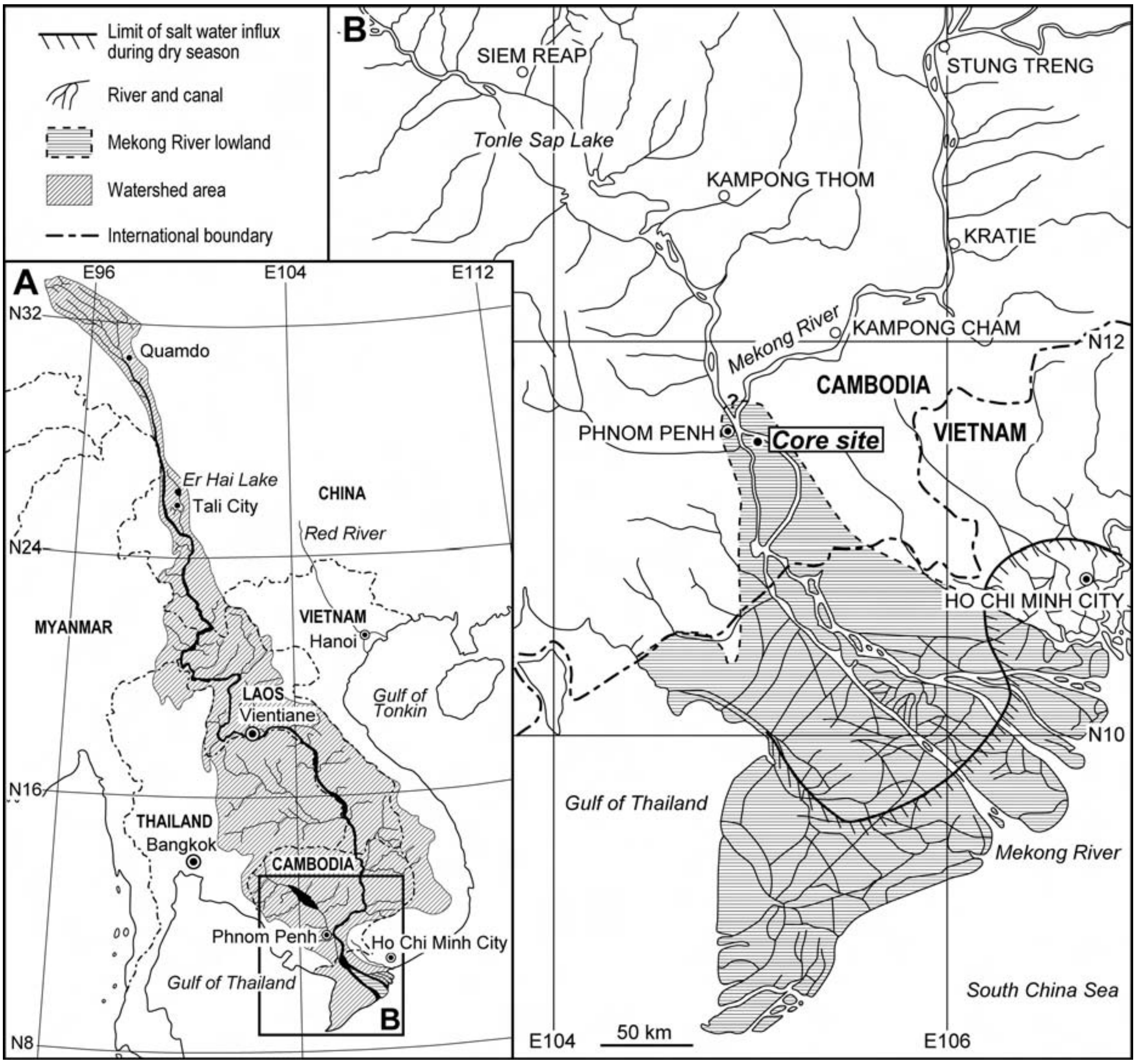

Fig. 1

Watershed area of the Mekong River (A), and location map of the Mekong River delta and KS core site (B). The core site is located near the upper boundary of the Mekong River delta area. The saltwater influx reaches several tens of kilometers inland from the present shoreline during the dry season. Redrafted after Hori (2000).

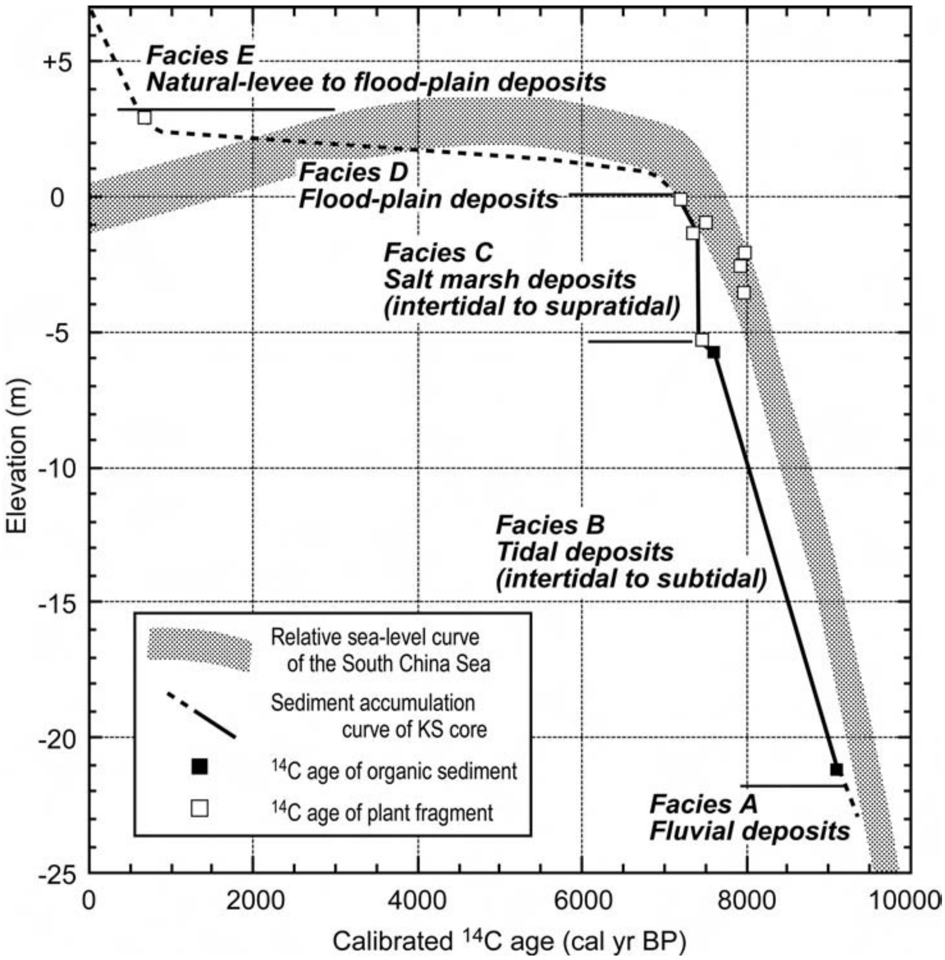

Fig. 2

Sediment accumulation curve of the KS core based on calibrated radiocarbon ages (Table 1) and the relative sea-level curve for the western margin of the South China Sea during the Holocene (compiled after Geyh et al., 1979; Tran and Ngo, 2000; Lam and Boyd, 2001). The Holocene relative sea-level change in this area is characterized by a rapid to slow rise and a subsequent stillstand and slight fall. The Facies B interval, tide-influenced estuary deposits accumulated during the rapid sea-level rise, is followed by deposition of salt marsh, flood-plain and natural-levee deposits (Facies C to E).

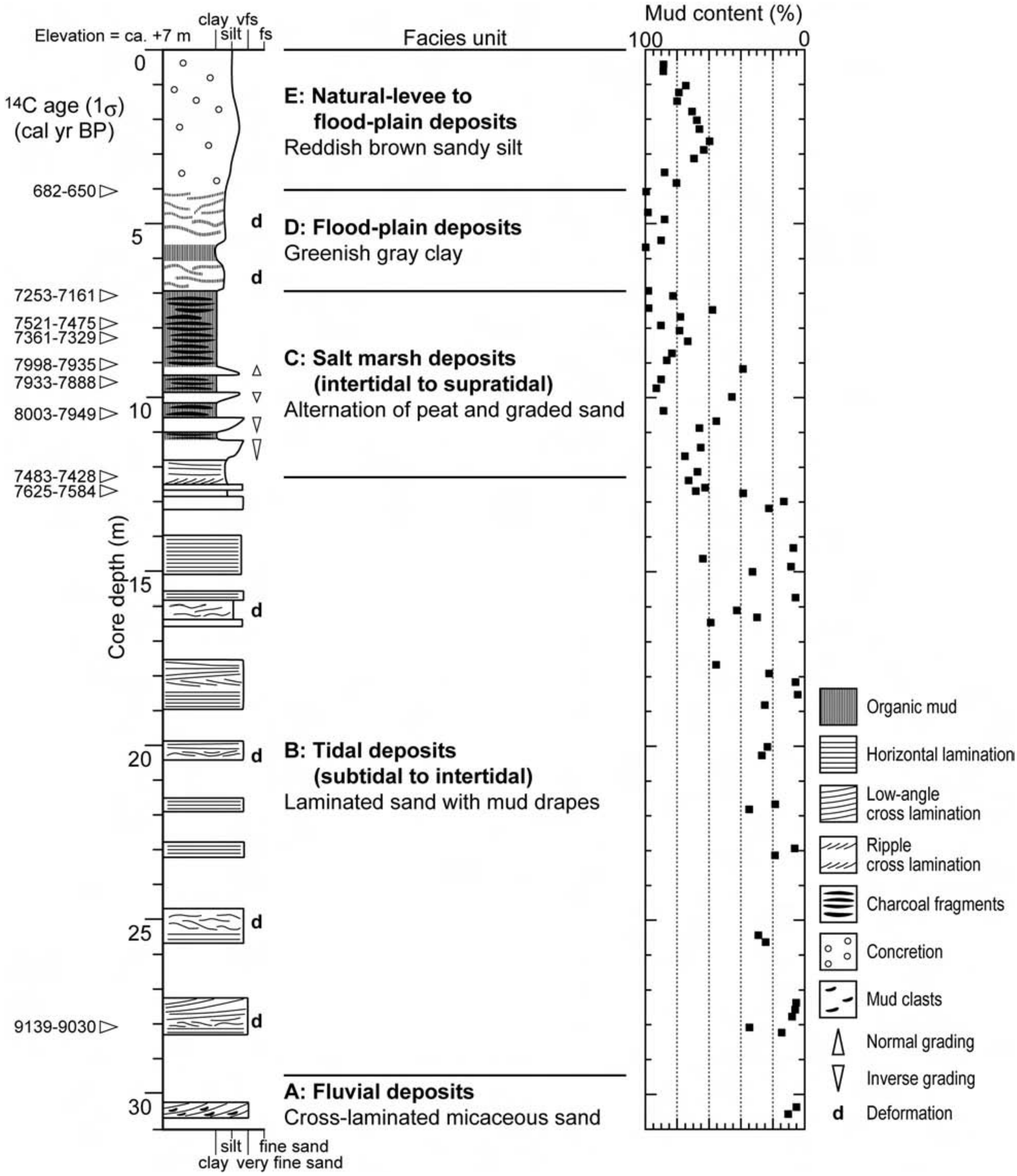

Fig. 3

Depositional facies and mud content of the KS core. The core penetrated five depositional facies, which are interpreted as fluvial, tide-influenced estuary, salt marsh, flood-plain and natural-levee deposits, in ascending order.

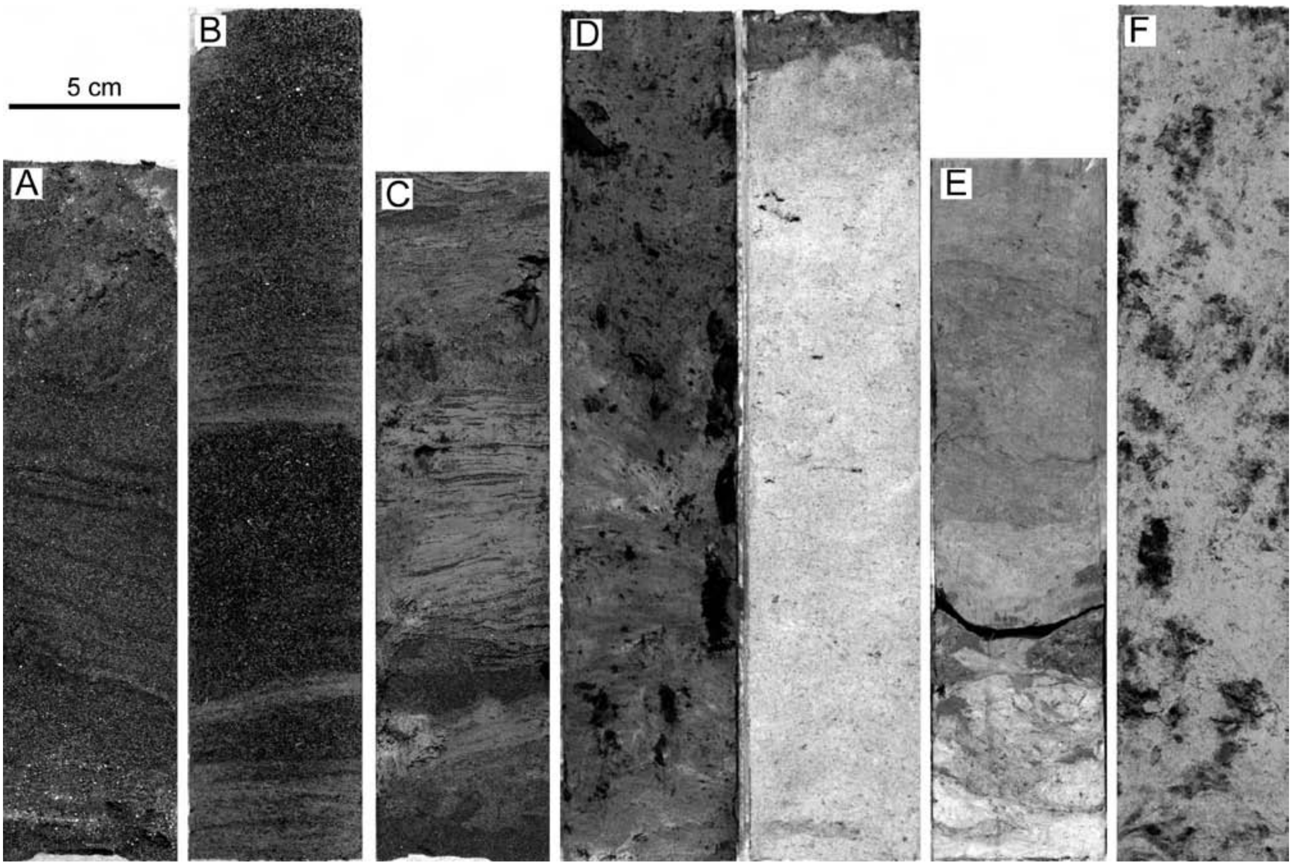

Fig. 4

Photographs of core sections. (A) Facies A, cross-laminated micaceous sand (core depth, 30.24–30.44 m); (B) the lower part of Facies B, horizontally laminated very fine sand with mud drapes (core depth, 21.59–21.84 m); (C) the uppermost part of Facies B, sandy silt with intervening thin, lenticular layers of very fine sand (core depth, 12.64–12.84 m); (D) Facies C, alternations of peat and graded sand layers; top upper left, base lower right (core depth, 9.59–10.09 m); (E) Facies D, organic, greenish gray clay (core depth, 5.60–5.80 m); (F) Facies E, reddish brown sandy silt (core depth, 1.30 –1.55 m).

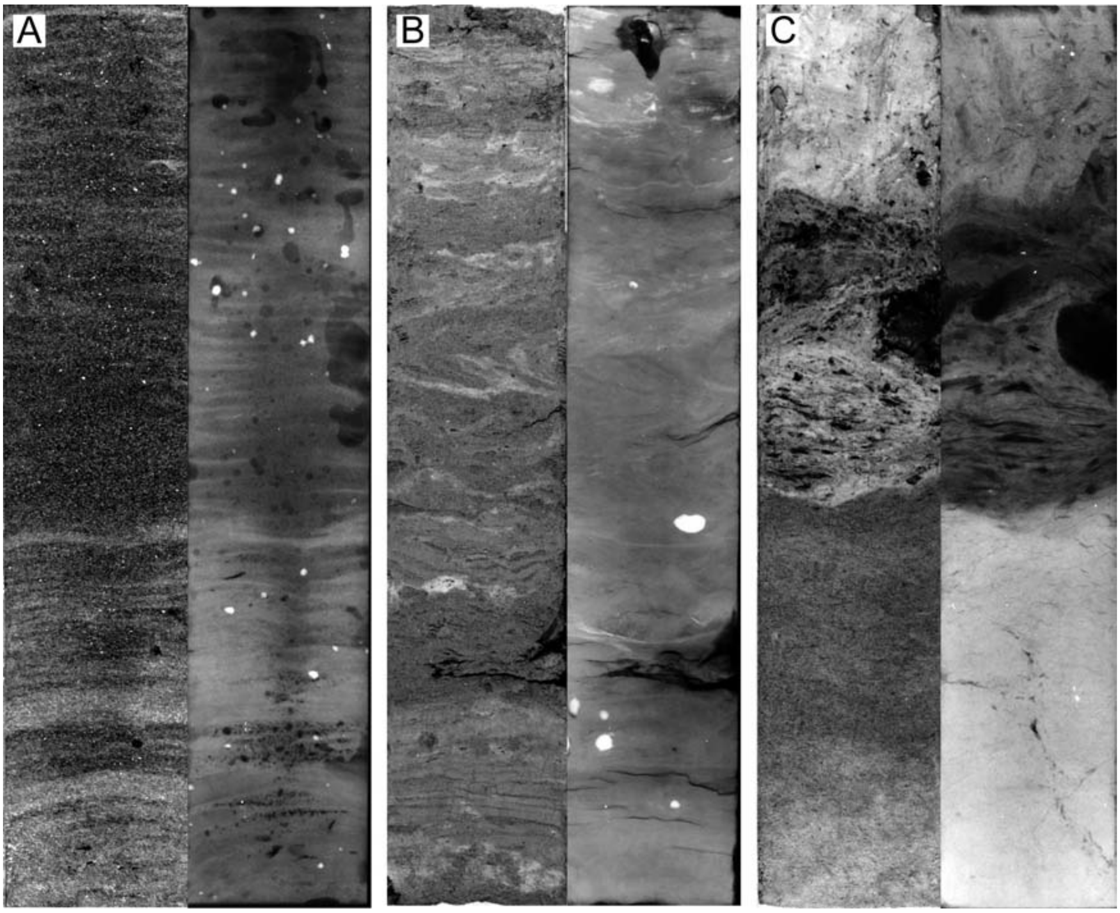

Fig. 5

Comparison between photographs (left) and soft X-radiographs (negative) (right) of the core. (A) The lower part of Facies B, horizontally laminated and mud-draped very fine sand (core depth, 18.64–18.89 m); (B) the uppermost part of Facies B, bidirectional ripple cross-lamination at the center of the section (core depth, 12.39–12.64 m); (C) Facies C, gradual transition from graded sand to peat (core depth, 8.99–9.24 m).